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Combining bottom trawl and acoustic data to model acoustic dead zone correction and bottom trawl efficiency parameters for semipelagic species

Stan Kotwicki, Alex De Robertis, James N. Ianelli, André E. Punt, and John K. Horne

Abstract: We present a modeling method that combines acoustic and bottom trawl abundance measurements and habitat data to estimate acoustic dead zone (ADZ) correction and bottom trawl efficiency parameters. Bottom trawl and acoustic measurements of walleye pollock (*Theragra chalcogramma*) abundance and available habitat data from the eastern Bering Sea are used to illustrate this method. Our results show that predictions of fish abundance in the ADZ can be improved by incorporating bottom habitat features such as depth and sediment particle size, as well as pelagic habitat features such as water temperature, light level, and current velocity. We also obtain predictions for trawl efficiency parameters such as effective fishing height, density-dependent trawl efficiency, and catchability ratio between trawl and acoustic data by modeling bottom trawl catches as a function of acoustic measurements and the environmentally dependent ADZ correction. We conclude that catchability of walleye pollock for either survey is spatially and temporarily variable. Our modeling method can be applied to other semipelagic species to obtain estimates of ADZ correction and bottom trawl efficiency parameters.

Résumé : Nous présentons une approche de modélisation qui combine des mesures d'abondance par relevé acoustique et au chalut de fond à des données sur l'habitat pour estimer les paramètres de correction pour la zone aveugle du faisceau acoustique (ADZ) et les paramètres relatifs à l'efficacité du relevé au chalut de fond. L'application de la méthode est illustrée à l'aide de mesures d'abondance de la goberge de l'Alaska (*Theragra chalcogramma*) provenant de relevés au chalut de fond et de relevés acoustiques et des données disponibles relatives à l'habitat pour l'est de la mer de Béring. Nos résultats démontrent que l'intégration de caractéristiques de l'habitat de fond comme la profondeur et la granulométrie des sédiments, ainsi que de caractéristiques de l'habitat pélagique comme la température de l'eau, l'intensité de la lumière et la vitesse du courant, peut améliorer les prédictions d'abondance de ce poisson dans l'ADZ. Nous avons également obtenu des prédictions des paramètres d'efficacité du relevé au chalut comme la hauteur de pêche effective, l'efficacité du relevé en fonction de la densité et le rapport de capturabilité entre les données de relevés au chalut et celles de relevés acoustiques en modélisant les prises au chalut de fond en fonction des mesures de relevés acoustiques et d'un facteur de correction pour l'ADZ dépendant du milieu. Nous en concluons que la capturabilité de la goberge pour l'un ou l'autre des types de relevé varie dans l'espace et dans le temps. Notre méthode de modélisation peut être appliquée à d'autres espèces semipélagiques afin d'obtenir des estimations du facteur de correction pour l'ADZ et des paramètres d'efficacité du relevé au chalut de fond. [Traduit par la Rédaction]

Introduction

Species that occupy demersal and pelagic habitats (hereafter referred to as semipelagic) are often surveyed using bottom trawl (BT) and acoustic trawl (AT) surveys (Karp and Walters 1994). Combining the abundance estimates from these two sampling methods is problematic because the biases associated with each method are unknown and inherently different (McQuinn et al. 2005). Consequently, abundance indices from both surveys are often treated as independent data sources in stock assessment, as is the case for walleye pollock (*Theragra chalcogramma*; hereafter referred to as pollock) in the eastern Bering Sea (EBS; Ianelli et al. 2009). Combined estimates from AT and BT surveys are desirable because they could provide a more accurate and precise abundance index for stock assessment and other studies (Godø and Wespestad 1993; Hjellvik et al. 2007). Combined estimates would also provide more accurate estimates of local density for spatial dynamics studies, spatial ecological models, and other studies that use abundance estimates or spatial density data (e.g., Spencer 2008; Ressler et al. 2012). However, combining estimates from the two survey types is difficult because of shortcomings of each survey method and the unknown catchability ratio between the two methods. The existence of the acoustic dead zone (ADZ) is a key concern when AT surveys (e.g., McQuinn et al. 2005) are used to estimate abundance of semipelagic species, because the part of the population that is close to the bottom is inaccessible to or undersampled by acoustic instruments (Ona and Mitson 1996). Although small when compared with the entire water column, the ADZ can contain a substantial fraction of the biomass of a semipelagic species. A BT survey is conducted for pollock to sample a part of the fish population that is present in the ADZ to mitigate the ADZ problem (Godø and Wespestad 1993). However, the BT survey has its own constraints that make the two data sets hard to directly compare or combine. This includes the inability to sample above the effective fishing height (EFH; Aglen 1996; Hjellvik

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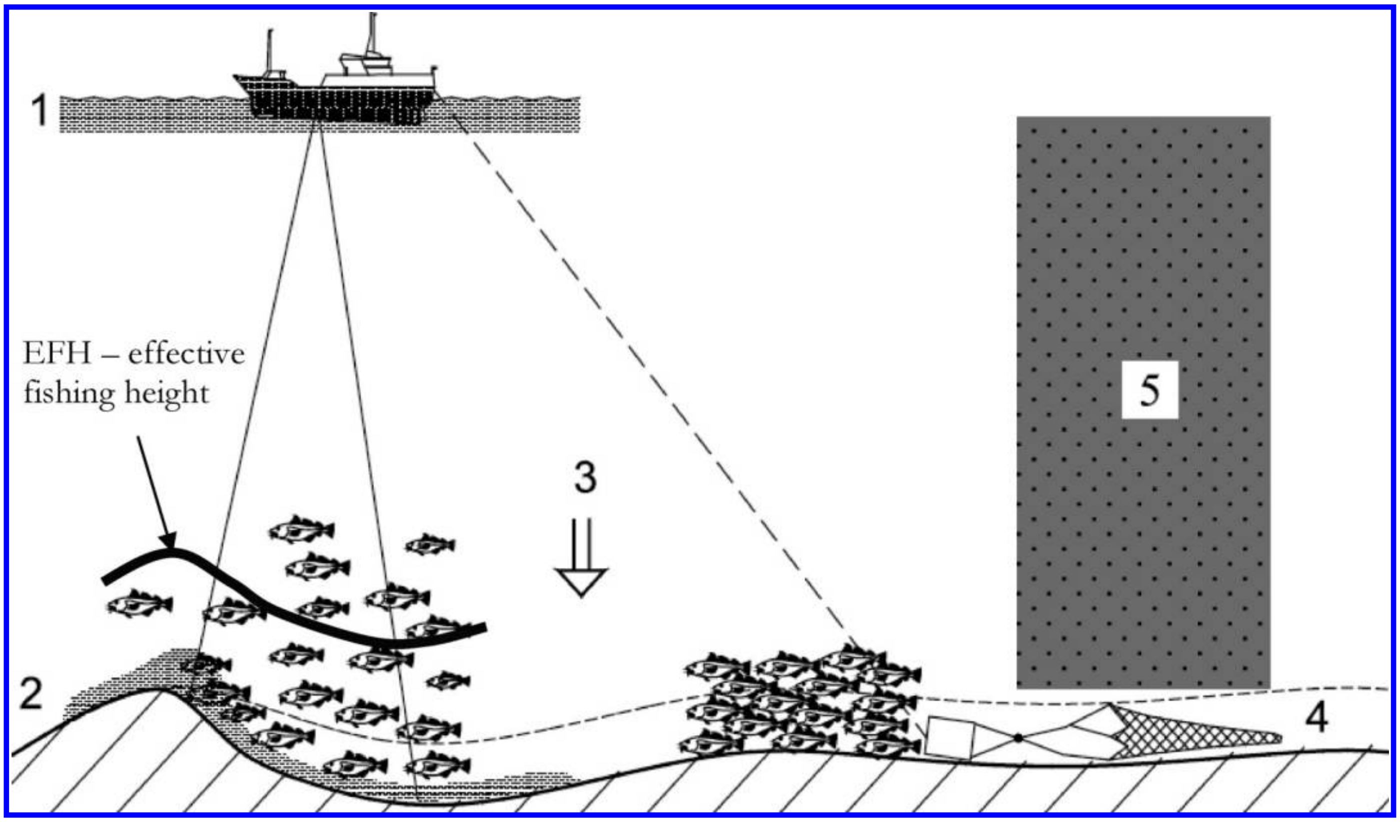
S. Kotwicki and J.K. Horne. National Marine Fisheries Service, Alaska Fisheries Science Center, National Oceanic and Atmospheric Administration, 7600 Sand Point Way NE, Seattle, WA 98115, USA; University of Washington, School of Fishery and Aquatic Sciences, Box 355020, Seattle, WA 98195, USA.
A. De Robertis and J.N. Ianelli. National Marine Fisheries Service, Alaska Fisheries Science Center, National Oceanic and Atmospheric Administration, 7600 Sand Point Way NE, Seattle, WA 98115, USA.
A.E. Punt. University of Washington, School of Fishery and Aquatic Sciences, Box 355020, Seattle, WA 98195, USA.
Corresponding author: Stan Kotwicki (e-mail: stan.kotwicki@noaa.gov).

Fig. 1. Illustration of the water column area sampled by the acoustic beam and in the volume swept of the bottom trawl (modified from Hjellvik et al. 2003). (1) The upper acoustic dead zone, (2) the acoustic bottom dead zone (ADZ), (3) vertical herding when fish are pelagically distributed above the bottom trawl, (4) the height of the trawl opening, and (5) the blind zone of the bottom trawl. The effective acoustic sampling is conducted in the area between 1 and 2. Note that the BT samples all the fish in the ADZ and some fish above it, while the acoustics samples all the fish above the ADZ.



et al. 2003), the unknown impact of fish responses to the vessel (Handegard and Tjøstheim 2009), the unknown catchability of the BT (Somerton et al. 1999), and possible density dependence of the efficiency of the BT (O'Driscoll et al. 2002; Hoffman et al. 2009).

In this study, we propose a modeling approach that combines simultaneously collected BT and acoustic data and environmental data to estimate the ADZ correction, BT efficiency parameters (EFH, density dependence), and the catchability ratio between acoustic and BT abundance estimates. Our approach builds on present understanding of the processes associated with the collection of fish abundance data from acoustics and BT given in Fig. 1. Acoustics detects fish in the water column between near-surface and near-bottom dead zones, while the BT detects fish that are near the bottom up to the EFH (Hjellvik et al. 2003). The near-surface acoustic dead zone is not a concern for a majority of semipelagic species because they are rarely in this zone, and we consequently use the term “ADZ” to refer to the near-bottom acoustic dead zone. Direct measurement of fish density in the ADZ is difficult. However, BT sampling can be used to estimate the density of fish near the seafloor. We obtain information about unknown processes (e.g., ADZ, trawl efficiency) associated with data collection by both methods by combining acoustic and BT data in one model. We have chosen semipelagic pollock from the EBS as a test case because it has been assessed using both BT and AT surveys since the 1980s (Ianelli et al. 2009). Both of these surveys detect substantial parts of the pollock population, indicating that pollock resides in both pelagic and near-bottom habitat (Kotwicki et al. 2005). Although the data used in this study are for EBS pollock, the method is broadly applicable to AT and BT surveys of other semipelagic or semidemersal species.

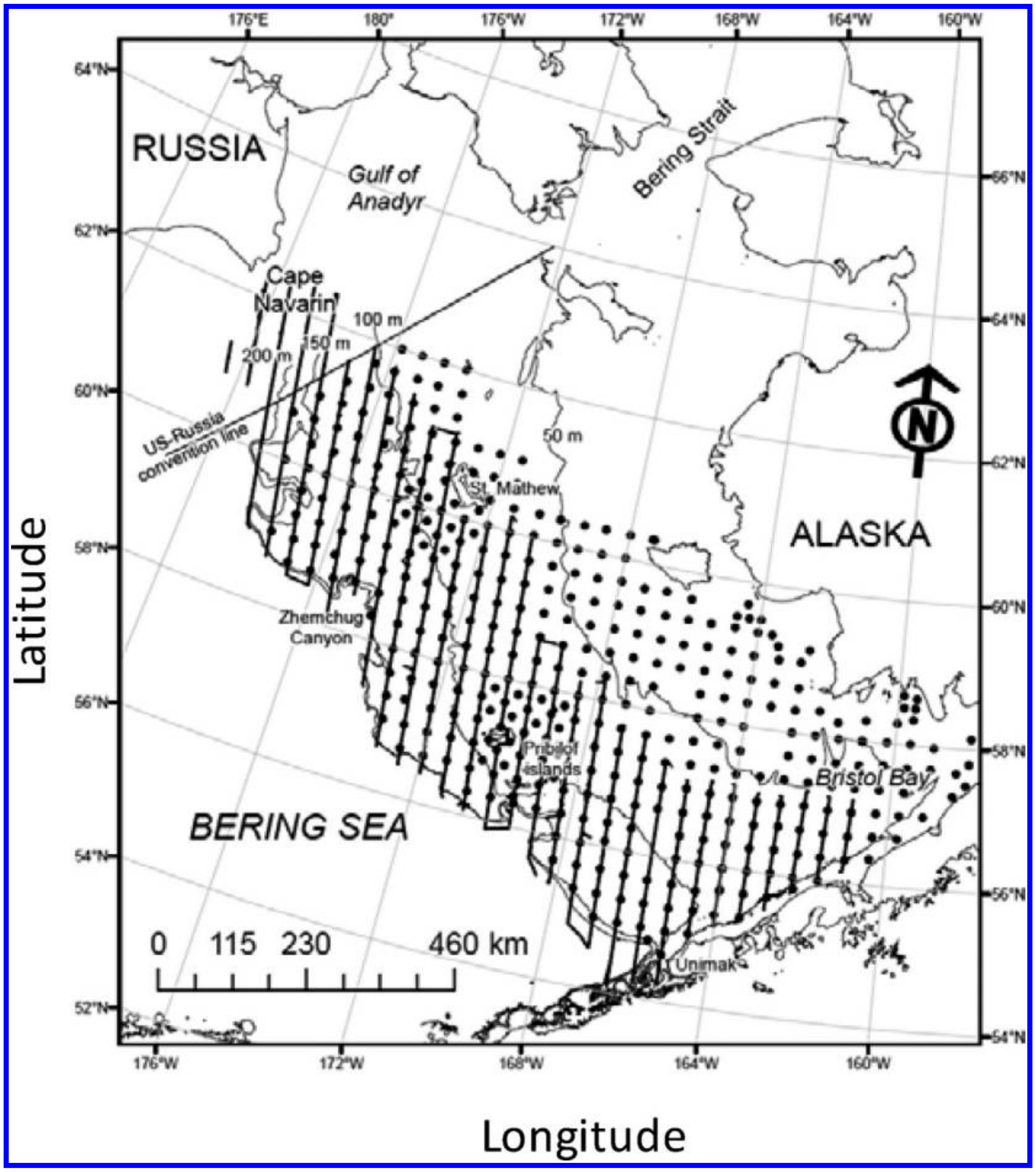
Methods

BT catch and acoustic data were collected during the annual EBS BT surveys conducted between 2005 and 2009 by the Alaska Fisheries Science Center (AFSC). The surveys were conducted using chartered fishing vessels (F/V *Aldebaran*, F/V *Arcturus*, and F/V *Northwest Explorer*) over the EBS, at the centers of a 20 n.mi. × 20 n.mi. (1 nautical mile = 1.853 km) grid (Fig. 2). The corners of the grids were also sampled in areas surrounding St. Matthew Island and the Pribilof Islands. The surveys were conducted in June and July and used the same standard trawl (83–112 eastern otter trawl; Stauffer 2004) during all years (Lauth 2010). Surveys started in the southeastern corner of the survey area and proceeded westward. Tow duration was approximately 30 min at 1.54 m·s^{-1} (3 knots).

Acoustic data

All survey vessels were equipped with 38 kHz Simrad ES60 split beam echosounders and 7-degree (between half power points) ES-38B transducers, which were calibrated twice during each survey using the standard sphere technique (Foote et al. 1987; Honkalehto et al. 2011). Echosounders used a 1 ms pulse length and a 0.5 m backstep above the sounder-detected bottom. Acoustic backscatter while vessel was trawling was processed using a semi-automated procedure (Kotwicki et al. 2009) to produce the nautical area scattering coefficient, s_A (a linear measure of backscatter per unit area; m^2·n.mi.$^{-2}$: see MacLennan et al. 2002), in bottom-referenced vertical layers. Layers between the echosounder-detected bottom and 5 m off bottom were integrated in 0.25 m increments, while layers above 5 m were integrated in 1 m intervals. A periodic and systematic error that can result in a maximum 1 dB (23%) difference in acoustic measurements made on individ-

Fig. 2. Bottom trawl (points) and acoustic (parallel lines) survey locations.



ual transmissions with the ES60 (Ryan and Kloser 2004; Keith et al. 2005) was removed by fitting the error to the otherwise constant transmit pulse and correcting the data. Acoustic data were recorded from the area directly below the vessel, while the BT was located approximately 100–300 m behind the boat. Additionally, the net may drift to one side of the boat during setting and towing, resulting in an additional offset (Engås et al. 2000). This approach resulted in a small offset between the location of the BT and the location of acoustic data collection as compared with the distance covered by the trawl (~2800 m) during a deployment.

To ensure that recorded backscatter was attributed to pollock, the 1934 candidate BT tows were examined for consistency. First, only catches where pollock made up at least 75% by mass of all pelagic fish in the catch (i.e., excluding flatfishes and skates) and where the pollock catch was >50 kg were further considered. Second, the backscatter data from 483 hauls meeting these criteria were examined to ensure that bottom integrations and artefacts such as noise spikes were excluded. In addition, a diffuse layer of surface-associated backscatter that did not contain adult pollock (De Robertis et al. 2008) was excluded from further processing by visually identifying the lower boundary of this layer. This depth ranged from 10 to 100 m and averaged 37 m below the surface. Third, 128 hauls with bottom integrations or a high degree of demersal backscatter that were not characteristic of pollock aggregations (i.e., attributed to aggregations of jellyfish or macrozooplankton) were also excluded from the analysis. This was done to minimize possibility of bias associated with the bycatch species that could have different trawl and acoustic vulnerability (e.g., O'Driscoll 2003). This left 355 tows with backscatter predominantly attributed to pollock to be used in further analyses.

BT catches

The areal density of pollock from BTs was estimated using the area-swept method (e.g., Alverson and Pereyra 1969). Area swept was estimated by multiplying distance fished, as indicated by bottom contact sensor (Somerton and Weinberg 2001), by the average distance between wing tips measured using Netmind spread sensors (see Weinberg and Kotwicki 2008 for details). After each tow, fork lengths for 150–200 pollock were measured to the nearest centimetre. The length frequency sample was then extrapolated to the entire pollock trawl catch. The catch per unit effort estimate at length (CPUE_L) was obtained using

$$\text{(1)} \qquad \mathrm{CPUE}_{L_i} = \frac{N_{L_i}}{A_i}$$

where N_L is a number of fish at length L in the catch, and A is the area-swept in n.mi.², and i indicates an individual tow. CPUE_L was then transformed into equivalent s_A ($s_{A,\mathrm{BT}}$) using the following formula (e.g., Doray et al. 2010):

$$\text{(2)} \qquad s_{A,\mathrm{BT}_i} = 4\pi \sum_L \mathrm{CPUE}_{L_i} \times 10^{\mathrm{TS}_L/10}$$

where

$$\text{(3)} \qquad \mathrm{TS}_L = 20 \log L - 66$$

is the experimentally derived target strength of pollock (Traynor 1996).

Predictor variables

Depth and temperature were measured during each trawl using a microbathythermograph (MBT) attached to the headrope of the trawl. Average bottom depth values were obtained by averaging MBT-detected headrope depth and Netmind-detected headrope height above the bottom over the duration of a tow. Near-bottom light levels were collected during each trawl using Wildlife Computers MK-9 archival tags (see Kotwicki et al. 2009 for details) mounted on the headrope of the BT. These tags provided relative values of near-bottom light levels every second that were then averaged over the duration of the trawl haul. Sediment size was estimated at each station using historical data from grabs and dredges (Smith and McConnaughey 1999) interpolated by ordinary kriging (Paul Spencer, AFSC, unpublished data). Sediment data were expressed in units of "phi" (Φ, negative $\log_2$ of the diameter in mm), where higher values correspond to smaller particle sizes (Wentworth 1922). Tidal current speed, to be used as a proxy of bottom current, was predicted for each tow using Oregon State University's Tidal Inversion Software (http://www.oce.orst.edu/research/po/research/tide/region.html; Egbert et al. 1994; Egbert and Erofeeva 2002). Mean fish length was calculated from length frequency samples using the following formula:

$$\text{(4)} \qquad \bar{l}_i = \frac{\sum_{L_i} N_{L_i} L}{N_i}$$

where N_{L_i} is total number of fish of length L in sample i, and N_i is total number of fish in sample i.

Model construction

We assume that a functional relationship exists between density estimates that are obtained from the acoustics and BT given that data collection took place simultaneously. We can specify this relationship as $s_{A,\mathrm{BT}} \sim f(s_A)$. The form of this functional relationship can be constructed using knowledge of the processes involved in acoustic data collection and BT catch. From Fig. 1 it can be deduced that BT equivalent s_A ($s_{A,\mathrm{BT}}$) can be predicted using acoustic backscatter that was detected above the ADZ up to the EFH plus unknown equivalent s_A in ADZ, which results in eq. 5:

$$\text{(5)} \qquad s_{A,\mathrm{BT}_i} = r_q\left(\sum_{b}^{\mathrm{EFH}} s_{A_i} + D_i\right) e^{\varepsilon_i}$$

where r_q is the catchability ratio between the BT and acoustics that accounts for differences in catchability between both methods, the EFH is defined above, D_i is the unobserved fish backscatter in the ADZ in s_A units (m²·n.mi.⁻²; thereafter referred to as the ADZ correction), b is the backstep in metres used in processing acoustic data, i is a tow subscript, and e^{ε} is lognormally distributed error. A lognormal error was assumed following Walters and Martell (2004), who argue that a lognormal distribution is appropriate because most quantitative observations in fish dynamics arise as a product of a model component and a proportional observation (r_q in this case), and the sum of logs of such proportions is likely to be normally distributed because of the Central Limit Theorem.

To determine the most appropriate model for relating acoustic and BT data, a set of alternative models was developed and compared using $\mathrm{AIC_c}$ (Akaike's information criterion corrected for finite sample size; Burnham and Anderson 2010). The first term in all models is of the same form as in eq. 5 and represents acoustic backscatter up to the EFH. The second term, which represents the ADZ correction, differs among models.

Model A

$$\text{(6)} \qquad s_{A,\mathrm{BT}_i} = r_q\left(\sum_{0.5}^{\mathrm{EFH}} s_{A_i} + D_{\mathrm{const}}\right) e^{\varepsilon_i}$$

Model A is the simplest with the ADZ term (D_{const}) independent of all covariates and constants. This type of model has been used in past attempts to estimate the EFH of the BT (e.g., Aglen, 1996; Rose and Nunnallee 1998; von Szalay et al. 2007).

Model B

$$\text{(7)} \qquad s_{A,\mathrm{BT}_i} = r_q\left(\sum_{0.5}^{\mathrm{EFH}} s_{A_i} + D_{u_i}(h)\right) e^{\varepsilon_i}$$

Model B has the ADZ term ($D_{ui}(h)$) independent of all environmental covariates; however, the ADZ term is not constant but rather determined by the backscatter observed immediately above the ADZ. This term represents the ADZ correction based on the geometric approach of Ona and Mitson (1996). This correction is appropriate for flat bottom areas (Patel et al. 2009) such as in the EBS and assumes that fish density in the ADZ is uniform (indicated by subscript u) from an acoustically visible layer just above the ADZ to the bottom. One improvement to the method incorporated here is the use of the observations to estimate the parameter h, which determines height of the acoustic layer that is used for ADZ correction and which is usually chosen arbitrarily.

To apply the Ona and Mitson (1996) ADZ correction, a theoretical height of the ADZ (h_{ADZ}) was estimated using the following formula:

$$\text{(8)} \qquad h_{\mathrm{ADZ}} = h_{\mathrm{eq}} + h_{\tau} + h_{\mathrm{b}}$$

where h_{eq} is equivalent lost height, h_{τ} is partial integration zone height, and h_{b} is the height of the backstep. h_{eq} is the height of the near-bottom layer that is lost because of the curved nature of the leading edge of the acoustic beam and equals $2.83 \times 10^{-3} \times \mathrm{BD}$ for a 7-degree beam, where BD is the bottom depth. h_{τ} is the height that is lost because of the inability to resolve backscatter associated with the bottom from backscatter associated with fish that are in close proximity to the bottom. This value depends on the length of transmitted pulse and equals $c\tau/4$, where c is the speed of sound, and τ is the pulse duration. h_b is the height of the zone above the echosounder-detected bottom that is used to avoid echo integration of the seafloor. This height has been set at 0.5 m to equal the value used in pollock AT surveys in the EBS.

Model C

$$s_{A,\mathrm{BT}_i} = r_q\left(\sum_{0.5}^{\mathrm{EFH}} s_{A_i} + e^{\boldsymbol{b}[\mathbf{X_i}]}\sum_{0.5}^{h} s_{A_i} + e^{\boldsymbol{c}[\mathbf{X_i}]}\right)e^{\varepsilon_i} \tag{9}$$

Model C has the ADZ correction term specified as

$$e^{\boldsymbol{b}[\mathbf{X_i}]}\sum_{0.5}^{h} s_{A_i} + e^{\boldsymbol{c}[\mathbf{X_i}]}$$

which represents an ADZ correction based on acoustic backscatter data up to height h (similar to Model B) as well as a constant parameter c (intercept in $\boldsymbol{c}[\mathbf{X_i}]$; similar to Model A). Inclusion of c was necessary because at times all fish caught by the BT were located in the ADZ, making it impossible to predict their density using s_A data exclusively. This model does not assume that fish density in the ADZ is the same as in the layer above. Instead, it assumes that fish density in the ADZ can be a function of s_A observed above the ADZ and environmental variables. This assumption seems reasonable in light of recent findings that density of pollock in the layers close to the bottom can be predicted using environmental variables (Kotwicki et al. 2009). Environmental variables and mean fish length are included in Model C as the linear covariates $\boldsymbol{b}[\mathbf{X_i}]$ and $\boldsymbol{c}[\mathbf{X_i}]$, where $\boldsymbol{b}$ and $\boldsymbol{c}$ are vectors of parameters, and $[\mathbf{X_i}]$ is a matrix of the predictor variables, including bottom depth, bottom temperature, surface temperature, sediment size, current speed, bottom light level, and mean fish length.

Model D

$$s_{A,\mathrm{BT}_i} = \left(\frac{1}{r_q\left(\sum_{0.5}^{\mathrm{EFH}} s_{A_i} + e^{\boldsymbol{b}[\mathbf{X_i}]}\sum_{0.5}^{h} s_{A_i} + e^{\boldsymbol{c}[\mathbf{X_i}]}\right)} + \frac{1}{a}\right)^{-1} e^{\varepsilon_i} \tag{10}$$

Model D is the same as Model C, but allows for density dependence in BT efficiency. The parameter a (estimated in backscatter units; $m^2 \cdot n.mi.^{-2}$) represents density dependence of the efficiency of the BT within the BT effective fishing zone, defined as the layer from the seafloor to the EFH. When fish densities are much lower than a, the term $1/a$ is negligible, and Model D converges to Model C. However, with increased fish density, a becomes more influential, resulting in reduced BT efficiency. For example, at fish density equal to the value of a, BT efficiency will be approximately half of the efficiency at lowest densities.

Model fitting

Model fitting was performed using maximum likelihood, assuming lognormal error with negative log-likelihood (NLL) function:

$$\mathrm{NLL} = 0.5N_\mathrm{T}\log(2\pi\sigma^2) + \frac{\sum_{i=1}^{N_\mathrm{T}}\left[\log(s_{A,\mathrm{BT}_i}) - \log(\widehat{s_{A,\mathrm{BT}_i}})\right]^2}{2\sigma^2} \tag{11}$$

where N_T is the number of tows, σ^2 is the error variance, and $\widehat{s_{A,\mathrm{BT}_i}}$ is the model prediction.

Model fitting was performed using Automatic Differentiation Model Builder (ADMB Project 2009). It was necessary to fit the model for all possible combinations of EFH and h and create a likelihood surface in relation to these parameters because EFH and h are not continuous (i.e., EFH and h represent heights of the discrete layers of integrated backscatter). Initial fitting indicated that this surface could be limited to the first 60 layers above the ADZ. Thus, 3600 model fits were required to obtain one likelihood surface. All four models were initially fitted to the acoustic and BT data, ignoring environmental predictors to compare the general performance of the models without performing variable selection in Models C and D at the same time. Backward variable selection was then undertaken for the linear predictors in the model that proved to be best among all models based on $\mathrm{AIC_c}$.

Model diagnostics

Model diagnostics were performed using residual analyses that included scatter plots of the observed values and standardized residuals versus predicted values, histograms of standardized residuals, normal Q–Q plots, standardized residuals versus predicted values and predictors, and ANOVA analyses of standardized residuals over time (with year as factor) and across vessels. Variance inflation factors (VIF) were also calculated for all linear terms in the final model to quantify the effects of possible multicollinearity in linear predictors (Kutner et al. 2004).

We also performed sensitivity analyses for possible bias in TS – fish length relationship. The 95% confidence bounds around the slope and intercept of this relationship (eq. 3) are 16.85 to 22.0 and –68.43 to –60.68, respectively (computed from the data in Traynor 1996). An error in this equation could affect abundance estimates derived from acoustic data (Godø et al. 1998) and values of $s_{A,\mathrm{BT}}$, which could affect our results in two ways. First, if either the intercept or the slope of this equation are biased, the estimate of parameter r_q would change. This effect would be of minor concern, because we treat abundance estimates from both data sources as relative indices of abundance, and the parameter r_q would still provide a means to combine or compare data from both surveys. Second, if the slope of the eq. 3 is biased, the relationship between fish density in the ADZ and mean fish length could be affected, which could be problematic in estimation of the ADZ correction. Therefore, we performed sensitivity analyses at the limits of the slope confidence bounds to assess to what degree this relationship could be affected by error in the slope of eq. 3.

Estimation of predictor effects

The relative impact of the linear predictors was determined using parameter estimates from the final model and mean values of all linear and nonlinear predictors estimated from the data. For example, the ADZ correction was calculated from the best model for all observed values of bottom depth, while all other predictors were fixed at their means to estimate relative effect of the bottom depth on the ADZ correction. All calculated ADZ values were then divided by their mean to show a change in ADZ correction relative to its mean value. These analyses were conducted for the ADZ correction factor and the BT-predicted catch.

Results

Model selection

Model D, which used both acoustic data as well as the intercept for the ADZ correction, had the lowest $\mathrm{AIC_c}$ score even without using environmental predictors (Table 1), indicating that Model D fit the data best among models examined. Since all four models have the same structure for the prediction of BT catches from the acoustic data, and they differ only in the form of the ADZ correction and density dependence, it can be concluded that the ADZ correction used in Model D performed best at predicting fish density in ADZ. Selection of Model D also indicated that inclusion of

Table 1. AIC_c and negative log-likelihood values for the four competing models.

	No. of parameters	Negative log-likelihood	AIC_c
Model A	4	419.26	844.59
Model B	4	442.60	893.27
Model C	6	370.65	751.46
Model D	7	361.36	734.96

Table 2. Estimates of the parameters of the final model with 95% confidence limits.

Parameter	Estimate	SD	Lower 95%	Upper 95%
r_q	0.9567	0.2385	0.4892	1.4242
a	4133.1000	1193.3000	1794.2320	6471.9680
σ	0.6116	0.0230	0.5665	0.6567
b_{BD}	0.0151	0.0031	0.0090	0.0212
b_{FL}	0.0023	0.0007	0.0009	0.0037
c_{BD}	−0.0138	0.0050	−0.0236	−0.0040
c_{ST}	0.3684	0.0629	0.2451	0.4917
c_{SS}	0.2656	0.0946	0.0802	0.4510
c_{BL}	−0.0073	0.0047	−0.0165	0.0019
c_{FL}	0.0013	0.0010	−0.0007	0.0033
c_{CS}	0.0020	0.0008	0.0004	0.0036
c	2.3322	0.9990	0.3742	4.2902
EFH	16 m		12 m	20 m
h	0.75 m		0.75 m	<1 m

Note: Parameters b are from the linear function $\boldsymbol{b}[\mathbf{X}]$, and parameters c are from the function $\mathbf{c}[\mathbf{X}]$. Predictors are indicated by subscripts: BD, bottom depth; FL, mean fork length; ST, surface temperature; BL, near bottom light; SS, sediment size; and CS, current speed. The confidence limits for the parameters h_1 and h_2 were obtained from a likelihood profile over h_1 and h_2; the confidence limits for remaining parameters are asymptotic approximations conditioned on the best estimates for EFH and h.

the parameter a, which accounts for density dependence in the efficiency of the BT, was appropriate.

Including environmental predictors in Model D improved the fit of the model to the data significantly by reducing the AIC_c by 51.72 (negative log-likelihood 329.16). Bottom depth, mean fork length, surface temperature, sediment size, bottom light, and current speed proved to be important predictors of fish density in the ADZ (detailed parameter values are presented in Table 2). Bottom temperature did not improve model fit, and it was eliminated from final model in variable selection process.

Model diagnostics

Diagnostic plots (Fig. 3) indicated that the assumption of log-normal error was appropriate. Visual examination of plots of standardized residuals against all predicted values and predictors (not shown) indicated that no apparent trends occurred in the residuals. ANOVA analyses of standardized residuals over time (with year as factor; Fig. 4) did not reject the null hypothesis that there were no temporal trends in residuals (p = 0.818). ANOVA analyses of standardized residuals between vessels indicated no vessel effect (p = 0.64). These results confirm that the form of the final model was appropriate. Estimates of VIFs were in the range of 1–2 (Table 3), indicating that multicolinearity of predictor variables had a small impact on inflating variance around predictor parameters (Kutner et al. 2004).

BT efficiency parameters

The parameters r_q, EFH, and a can be used to describe BT efficiency relative to observed acoustic backscatter in the effective fishing zone and predicted fish density in the ADZ because they provide information necessary to relate the two types of data. The estimate of EFH indicates that the BT on average captures fish up

Fig. 3. Diagnostics plots for the final model: (a) scatter plot of log(observed) vs. log(predicted); line represents $y = x$ relationship; (b) scatter plot of standardized residuals vs. log(predicted); line represents a loess smooth going through the data; (c) histogram of standardized residuals; (d) a Q–Q plot showing sample quantiles (obtained from standardized residuals) vs. theoretical quantiles of normal distribution.

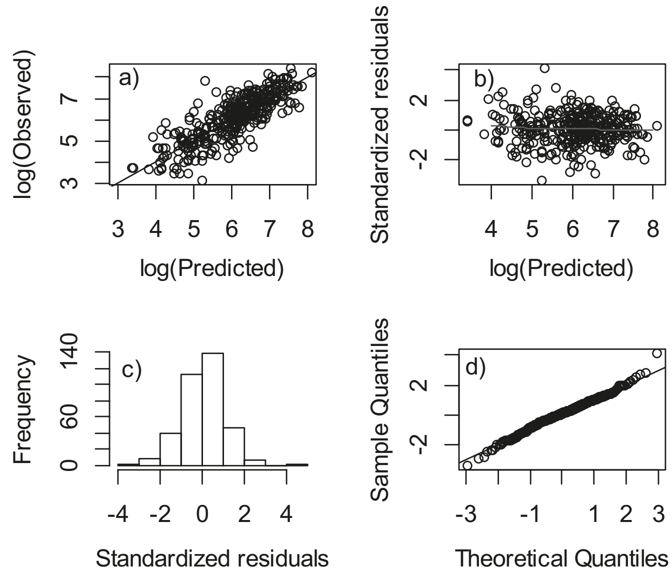
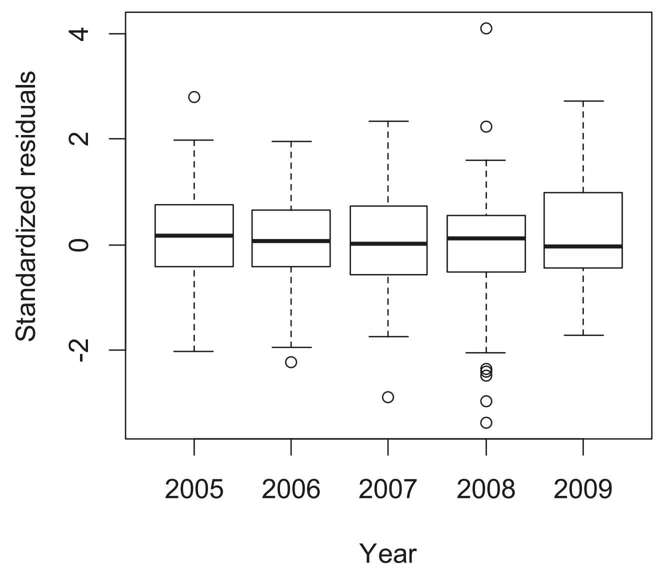
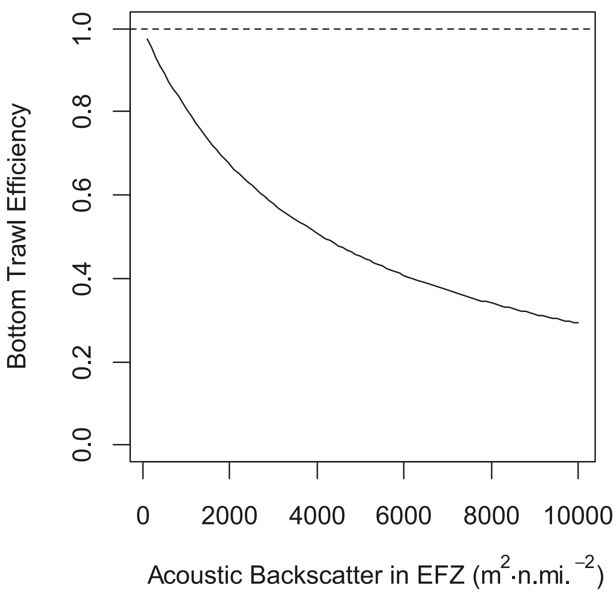


Fig. 4. Standardized residuals from Model D by year. Box upper and lower boundaries represent upper and lower quartiles. Whiskers represent maximum and minimum values except outliers (circles), which are defined as points with values greater than 1.5 times the lower and upper quartiles.



to 16 m above the bottom. The estimate of r_q was 0.96 and not significantly different from 1, indicating that the catchabilities of the two surveys are effectively the same. However, the catchabilities are comparable only at low densities because the estimate of a = 4133 implies that BT efficiency is reduced at higher densities (Fig. 5). For example, the BT will be only half maximum efficiency at fish densities equivalent to the value of a (or ~778 911 fish·n.mi.$^{-2}$ assuming 40 cm fish length). Such a density will result in an estimated pollock catch of approximately 3 metric tonnes (t) during

Fig. 5. Predicted bottom trawl efficiency (*a*) and predicted bottom trawl catches (*b*) as a function of acoustic backscatter in the effective fishing zone (EFZ; solid lines). Dashed lines on both panels indicate density-independent efficiency. 1 nautical mile (n.mi.) = 1.853 km.



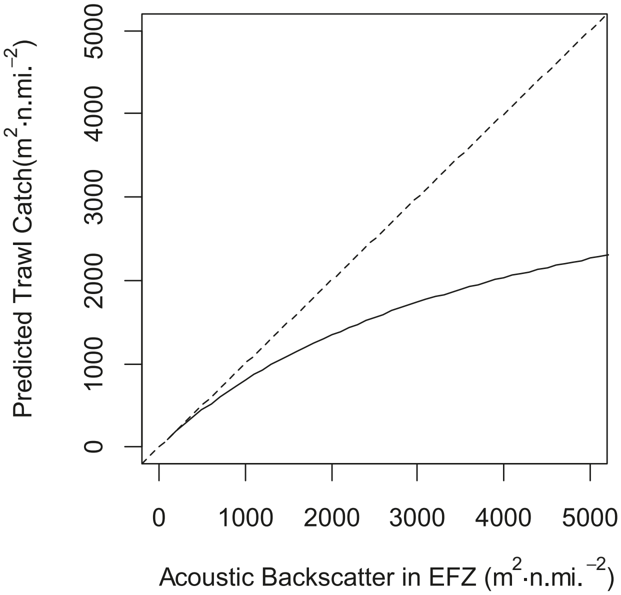


Table 3. Variance inflation factors (VIF) for the linear predictors included in the final model.

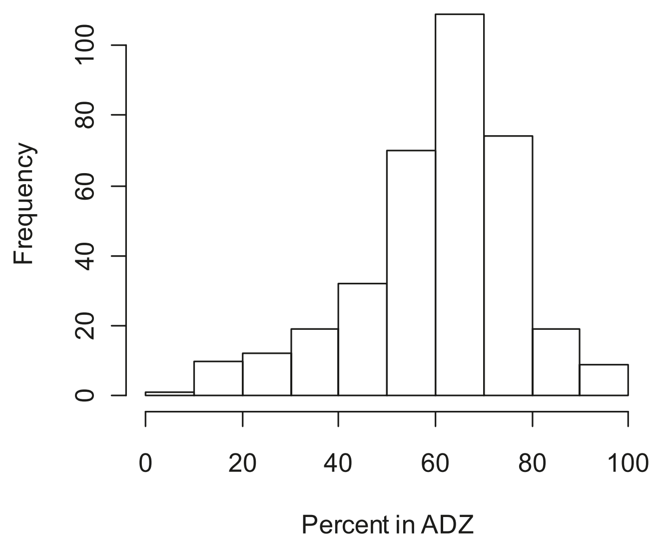
Linear predictor	VIF
Bottom depth	1.80
Surface temperature	1.46
Sediment size	1.73
Bottom light	1.14
Fork length	1.28
Current speed	1.19

30 min tow; catches of this size (and greater) occurred on average in 2.5% of tows in EBS BT surveys.

ADZ correction parameters

Estimates of pollock densities in the ADZ confirmed our expectations that a large proportion of EBS pollock may be located in the ADZ. ADZ corrections for the stations used in this analysis ranged between 8% and 97% (mean 60%, median 63%) of all the fish in the entire water column (Fig. 6). The estimate of *h* indicates that fish density in the ADZ is predicted best using acoustic backscatter data from the first layer above it. Our results also indicate that predictors such as environmental variables and fish length can be used to predict fish density in the ADZ. Assessment of these predictors over the range of observed environmental variability is presented in Fig. 7. Low estimates of VIFs indicated that possible correlations between predictor variables are not of a concern. Bottom depth was by far the most influential environmental predictor for fish density in the ADZ, and its effect ranged from ~0.6 of the mean prediction in the shallowest depths of 40–60 m to 2 at the depths of 160 m (Fig. 7*a*). The surface temperature effect increased from 0.8 to 1.5 over 2 to 10 °C (Fig. 7*b*). Pollock densities in the ADZ increased from 0.9 to 1.2 relative to the mean as sediment size decreased from 1 to 7 phi (Fig. 7*c*). Increasing light levels decreased pollock densities in the ADZ (Fig. 7*d*). Inclusion of current speed in the model was supported by AIC_c, but this variable had a minor effect on pollock densities in the ADZ (Fig. 7*e*). On the other hand, an increase in mean pollock length led to large increases in the density of pollock in the ADZ (0.6 for the smallest

Fig. 6. Histogram of the model-predicted biomass in the acoustic dead zone (ADZ) as a proportion of the entire water column for all trawl stations (*n* = 355) used in analysis.

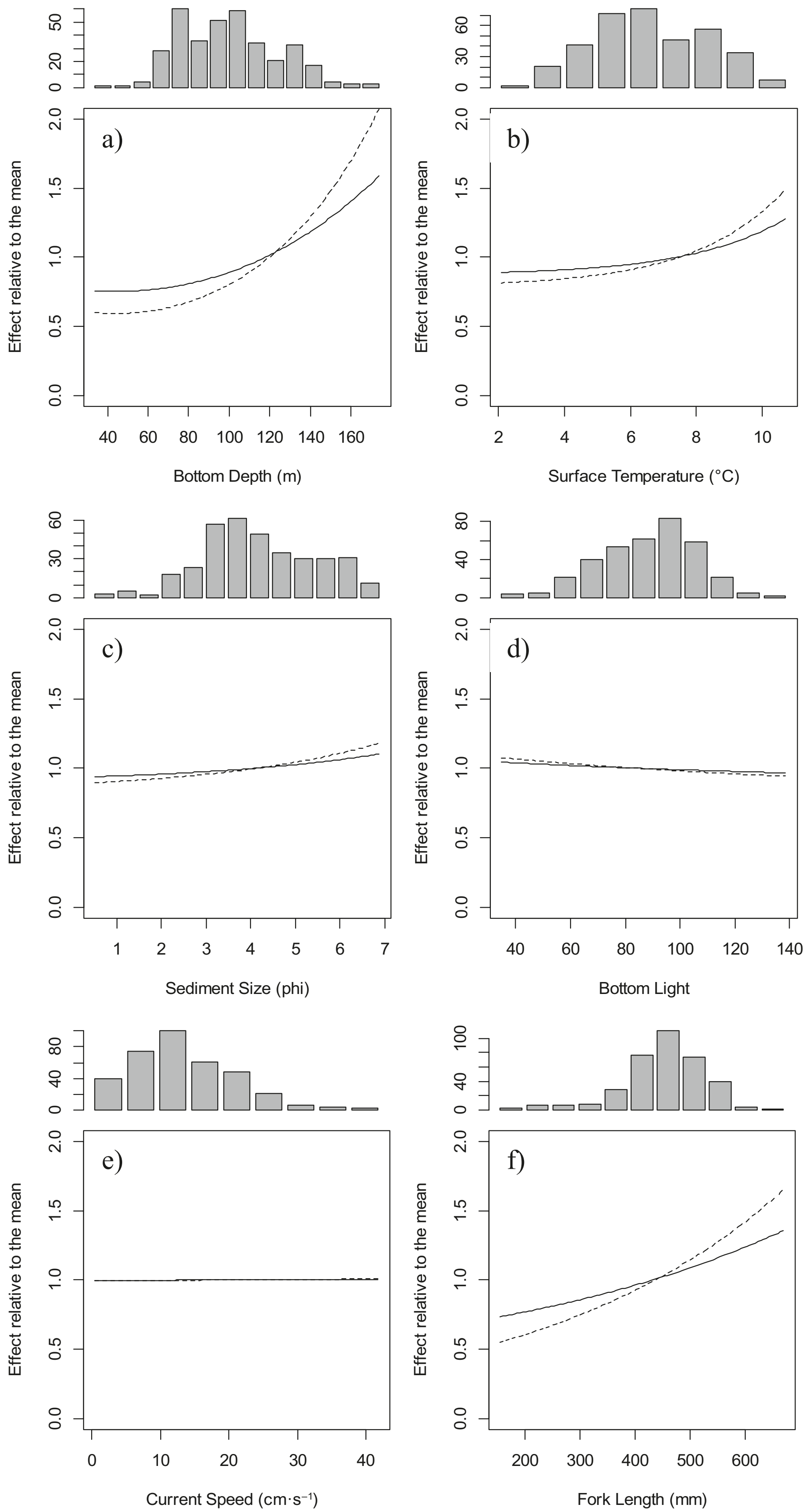


pollock (~20 cm fork length) to 1.60 for the largest pollock (>60 cm fork length); Fig. 7*f*).

Environmental effects on BT catch

Predictions of BT catch at a given s_A in the effective fishing zone indicated that environmental variables and fish size had a substantial effect on predicted BT catches (Fig. 7). Bottom depth was the most influential environmental predictor for BT catches, and its effect ranged from ~0.75 of the mean in the shallow depths to 1.5 in the deep areas covered by the survey (Fig. 7*a*). The effect of surface temperature effect varied from 0.9 to 1.2 over the range of observed temperatures (Fig. 7*b*). Decreasing sediment size had an increasing effect on BT catches from 0.9 to 1.1 of the mean (Fig. 7*c*). Increasing light levels decreased pollock catch from 1.05 to 0.95 (Fig. 7*d*). The effect of current speed on BT catch was minimal (Fig. 7*e*). Standardized pollock catch in the BT increased from 0.75 for the smallest pollock (~20 cm length) to 1.30 for >60 cm

Fig. 7. Relative effects of environmental variables and mean pollock length on predicted areal densities in the acoustic dead zone (dashed line) and bottom trawl catches (solid line). Effects were estimated relative to the mean predictions in the range of observed environmental variability presented in the histograms.



pollock (Fig. 7*f*). The sensitivity analysis for inaccuracies in the TS ~ fish length (eq. 3) indicated that for any value of the slope within confidence bounds, the relationship between ADZ fish density and fish length remains monotonically increasing (data not shown).

Discussion

Interpretation of model selection

Best fit to the data by Model D indicated that the catchability of either BT or AT survey for pollock is variable in space and time because it depends on environmental variables and is density-dependent in the case of the BT survey. However, it is likely that environmental variables are affecting catchability indirectly by impacting fish distribution patterns and behavior. Similar conclusions have been reported by Godø and Wespestad (1993), where they state that the "survey conditions" or environmental impacts on distribution patterns impact catchability differently from year to year. Additinally, Aglen et al. (1999) found environmentally driven variable availability and efficiency of the BT and variable availability to an echosounder for Atlantic cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*), and redfish (*Sebastes* spp.). These studies indicate that achieving constant survey catchability across time and space for semipelagic species may be impossible regardless of survey standardization efforts (Stauffer 2004). Catchability is unknown for most fishery-independent surveys, but it is assumed to be stationary in time and space (Kimura and Somerton 2006) because survey data are often perceived to be of better quality than fishery data (Harley et al. 2001). Our findings indicate that problems associated with nonstationary catchability in the fishery-dependent data (i.e., commercial fishery data; e.g., Godø and Engås 1989; Hilborn and Walters 1992; Wilberg et al. 2010) may also arise with survey data. This can be problematic, for example, in geostatistical estimates of fish abundance because they require that underlying local CPUE data are proportional to abundance (Rivoirard et al. 2000). The fact that local CPUE data from either the AT or the BT survey may not be proportional to fish density can introduce errors in these estimates. The same assumption is often made in spatial dynamics studies, which use CPUE data to investigate relationships between fish distributions and environmental factors (e.g., Bartolino et al. 2011). In the case of these studies, the presence of nonstationary, environmentally dependent catchability makes it impossible to distinguish environmental effects on fish spatial distribution from environmental effects on catchability. This conundrum can be resolved by combining results from two surveys, conducted simultaneously, in a model that accounts for factors influencing both surveys as was presented here. In the EBS pollock example, the models predicted an ADZ correction and BT efficiency parameters. The next logical step will be to use these results to estimate environmental effects on catchability and correct local density estimates for environmental effects, thereby providing spatial distribution data that is reflective of actual species distributions.

BT efficiency parameters

One of the main goals of this study was to estimate BT efficiency parameters. These parameters are needed when combining acoustic and BT survey data, but they should be especially useful in years when only a BT survey was conducted. In the case of pollock in the EBS, BT surveys are conducted annually, while AT surveys occur on a biennial schedule (Ianelli et al. 2009).

Efficiency of a BT

Selection of Model D indicates that the BT does not capture fish in proportion to their abundance in the effective fishing zone. Declining survey BT efficiency with increasing fish density has also been observed by Hoffman et al. (2009) for Atlantic croakers (*Micropogonias undulatus*) and white perch (*Morone americana*) in Chesapeake Bay and earlier by O'Driscoll et al. (2002) for capelin (*Mallotus villosus*) off Newfoundland. These findings contradict those reported by Godø et al. (1999), who deduced, from observations of Atlantic cod and haddock, that BT efficiency should increase with increased density. However, Godø et al. (1999) acknowledged that their study was limited to observations of fish behavior in close proximity to the opening of the trawl and did not account for fish behavior over the entire area between the vessel and the trawl.

Density dependence of BT efficiency can be troublesome to stock assessment because it suggests that pollock CPUE from the BT survey may be hyperstable (Hilborn and Walters 1992). Hyperstability implies that detected changes in fish abundance are smaller than actual changes, and it occurs commonly in fishery-dependent data (e.g., Harley et al. 2001). In certain cases it could, if not accounted for, contribute to management decisions that lead to stock collapse, as it did for the northern cod stock (Hutchings 1996; Walters and Maguire 1996). Fishery-independent surveys have been thought to avoid hyperstability problems (e.g., Harley et al. 2001); however, our findings suggest that this assumption may not always be accurate. The effect of hyperstability on CPUE could be dampened by accounting for corrections based on simultaneously collected acoustic data, since these data are likely not hyperstable because of the linearity principle of echo integration (Foote 1983) and negligible acoustic shadowing effect (Zhao and Ona 2003) at the backscatter levels observed for pollock in the EBS.

EFH (vertical herding)

EFH of BTs has been a topic of recent research (Aglen 1996; Hjellvik et al. 2003; Handegard and Tjøstheim 2009). Our study indicated that average EFH for pollock in the EBS was about 16 m. This result differs from that reported by von Szalay et al. (2007), who concluded, from a model similar to our Model A, that the effective net height was equal to the measured net height. Their conclusion is not supported by data used in this study, as Model A performed significantly worse than Models C and D. An EFH of 16 m compared with a 2.4 m mean headrope height (von Szalay and Somerton 2009) implies that pollock dive in response to the passing boat and (or) trawl warps. This conclusion confirms the findings of Rose and Nunnallee (1998), where correlations between BT and acoustic data indicated a pollock diving response to the BT. A diving response to an approaching trawl was also observed for other semipelagic species, including haddock (Ona and Godø 1990) and Atlantic cod (Handegard et al. 2003; Handegard and Tjøstheim 2005).

Catchability ratio

The catchability ratio parameter r_q is important when data from the AT or BT survey need to be provided on the same scale. For example, estimating spatial distribution using both AT and BT survey data are possible only if the ratio of catchability for the two gears is known. Without this information, distributions from combined surveys would be positively biased to the survey with higher catchability. Similarly to the EFH, which is regarded as the extent of pollock vertical herding, r_q can be thought of as quantifying horizontal herding by BTs. BT doors and bridles create mud clouds that can herd fish into the path of the trawl (Engås and Godø 1989; Dickson 1993). The r_q estimate in our best model was not significantly different from 1, which indicated that horizontal herding of pollock by the EBS survey BT is not strong, and densities that are detected by a BT survey are similar to those detected by an AT survey (assuming that pollock TS – fish length relationship is not biased). This conclusion is consistent with the findings of Somerton (2004), who did not observe horizontal herding of pollock or Pacific cod (*Gadus macrocephalus*) in response to a BT in the Gulf of Alaska.

The inclusion of the EFH parameter together with the catchability ratio in one model could create a potential for confounding (i.e., an increase in one of the parameters would cause a decrease in the other) when acoustic densities exhibit similar vertical distributions. However, variability in vertical distribution (in the data) provided enough information to prevent confounding between these parameters, because the EFH is affected by vertical distribution in a different way than the catchability ratio. The relatively tight confidence bounds around each of the two parameters indicate that they are not strongly confounded.

Specific parameter values obtained in our study could be different if we had used acoustic data from a free-running survey vessel (speed ~3 knots) instead of trawling vessel (speed ~10 knots). To date, two studies have been performed to compare pollock s_A from free-running versus trawling vessels. De Robertis and Wilson (2006) found that s_A from a free-running vessel was significantly higher than that from a trawling vessel by approximately 20%. On the other hand, von Szalay and Somerton (2009) found that s_A from the free-running vessel was significantly lower than that from a trawling vessel by approximately 30%. These contrasting results indicate that the relationship between trawling and free-running s_A could be specific to the vessel–trawl combination (von Szalay and Somerton 2009). In such a case, it would be prudent to perform experiments collecting data from a free-running AT survey vessel and a trawling BT survey vessel (e.g., paired comparisons) to obtain specific vessel-to-vessel parameter estimates. Moreover, De Robertis and Wilson (2011) showed that changes in fish behavior in time and space could also result in different backscatter readings from the same vessel. Although this spatio-temporal variability in how pollock behave when they encounter a survey vessel may have contributed to the unexplained deviance seen in our models, given that model residuals are similar among years (Fig. 4), there do not appear to be any major interannual changes in pollock behavior.

ADZ correction

Our results indicate that acoustic backscatter combined with other predictors, such as environmental variables and fish size, can be used to predict fish density in the ADZ. The value for the parameter h indicates that fish density in the ADZ is best predicted using acoustic backscatter data from the first sampled layer above ADZ. This is similar to the method proposed by Ona and Mitson (1996), but does not assume that fish density in the ADZ is equal to that in the first layer. Our experimentally derived ADZ correction assumes that fish density in the ADZ is a linear function of s_A in the layer just above the ADZ, and both the slope and the intercept of this function can be determined using other variables that may affect actual fish density in the ADZ.

Since Ona and Mitson (1996) showed how to theoretically estimate the lost sampling volume associated with the ADZ, their correction has been widely used to correct acoustic density estimates (e.g., Rose 2003; McQuinn et al. 2005; Kotwicki et al. 2009). However, the method makes two assumptions. The first assumption is that the ADZ height is based on a flat seafloor over the footprint of the acoustic beam. In reality, the theoretical ADZ can differ from the dead zone height because of seabed slope and topography (e.g., Kloser et al. 2001; Patel et al. 2009), the angle of incidence of the beam on the seafloor (which is influenced by transducer motion; Mello and Rose 2009), or inaccurate bottom detections (MacLennan et al. 2004). The second assumption is that fish density in the ADZ is equivalent to the density immediately above the ADZ. This assumption may be violated in the case of semipelagic species (e.g., Lawson and Rose 1999; Rooper et al. 2010) because of greater affinity of these species to the seafloor. Lastly, there is an ambiguity in choosing the height of the layer just above the ADZ to correct the ADZ. All of these assumptions were not necessary in Model D, which estimated ADZ correction empirically based on the data collected from BT.

Comparison of Models B and D indicated that an empirically estimated ADZ correction is preferable to a theoretical value. Moreover, better performance of Model A compared with Model B indicated that using a simple constant for an ADZ correction may be more appropriate than using one based on sampling geometry alone. This finding suggests that the density of pollock in the ADZ is rarely the same as in the layer just above it. It also indicates that models for ADZ correction should be tested empirically.

Environmental effects

This investigation provides evidence that the density of pollock in the ADZ depends on many environmental factors and shows that s_A alone is a rather poor predictor of fish density in the ADZ. Semipelagic fish behavior in the water column can be affected by fish size as well as environmental factors (e.g., Michalsen et al. 1996; Aglen et al. 1999; Kotwicki et al. 2009). Changes in behavior may influence fish vertical distribution close to the bottom and hence abundance in the ADZ. Therefore, it is preferable to use the experimentally derived ADZ correction,which accounts for environmental effects, over one that uses a geometric approach exclusively.

Higher fish abundance in the ADZ with depth is expected because the volume of the ADZ increases with depth (Ona and Mitson 1996). The surface temperature effect detected in the model (Fig. 7*a*) may be explained by pollock avoidance of warmer temperatures that would result in increased need for oxygen and food consumption (Clarke and Johnston 1999). In the EBS, areas with high surface temperatures have a greater vertical temperature gradient than areas with colder surface temperatures. Pollock, therefore, may have more incentive to be near the bottom (in colder water) in areas with a higher surface temperature to conserve energy. Additionally, zooplankton availability in the water column generally decreases in the EBS by the end of summer (Springer et al. 1989; Chuchukalo et al. 1996; Coyle et al. 1996), indicating that this energy-saving behavior may be reasonable when surface temperatures are highest. The model predicted higher fish densities in the ADZ with decreasing sediment size ranging from sand to mud. A possible explanation may be that pollock prefer to be closer to the sandy mud bottom, prevalent on the middle EBS shelf (Smith and McConnaughey 1999), because of higher food availability on the inner shelf with 10-fold larger infaunal biomass than on the outer shelf (Walsh and McRoy 1986). Our study also predicted that pollock density in the ADZ is lower with increased near-bottom light levels. This finding seemingly contradicts a previous study on the effect of light on pollock vertical distribution, which indicated that pollock tend to be higher off the bottom in low, near-bottom light conditions (Kotwicki et al. 2009). However, this study did not look explicitly at the ADZ, but only at pollock observed by the acoustics. Lastly, although current speed was selected (based on AIC_c), the magnitude of the current speed effect proved to be very small, and at this point we consider it negligible. Future research, using methodology presented here, could explore additional environmental factors that are likely to influence pollock densities in the ADZ.

Our study also found a size-dependent effect with pollock abundance in the ADZ, with larger pollock more likely to be present in the ADZ. This result was expected because larger pollock are more demersal (Karp and Walters 1994). Also, survey selectivity curves derived in pollock stock assessments show that the selectivity of the AT survey is lower for larger pollock (Ianelli et al. 2009), suggesting that larger pollock are more likely to be present in the ADZ.

Implications for stock assessment

Looking forward, we advocate that combined acoustic–bottom trawl survey to be considered in place of the separate AT and BT surveys to minimize possible biases associated with environmental variability (Godø and Wespestad 1993). If the surveys are performed on separate vessels, it is important to schedule them at approximately the same time and location. Both AT and BT surveys have shortcomings that can complicate interpretation of survey abundance data. In the AT survey, the ADZ causes bias (e.g., McQuinn et al. 2005) and can lead to spatial and temporal changes in the AT survey catchability (Kotwicki et al. 2009) because of the dependence of the fish density in the ADZ on environmental variables. In the case of the BT survey, the existence of a BT blind zone (Fig. 1) and density dependence of BT catches indicate similar bias and catchability problems. However, performing both surveys on one platform and using models such as the one presented here could mitigate these problems. Further research on the models that quantify the ADZ correction incorporating environmental factors and BT efficiency parameters could concentrate on two aspects that have been shown here but remain still unresolved. First, variability in catchability of both AT and BT surveys needs to be better understood. Parameters estimated in models that combine BT and acoustic data could provide the means to estimate changes in catchability of either survey in relation to environmental factors, allowing estimation of the magnitude of these effects on survey abundance indices. Second, this knowledge would also be useful for deriving one abundance index by combining results from both BT and AT surveys and testing these new indices in stock assessment models.

Ecosystem monitoring to better understanding ecosystem patterns and processes is a dominant theme of the ecosystem-based approach to management (Grumbine 1994; Christensen et al. 1996; Mangel et al. 1996). However, our understanding of the abundance of key organisms in the ecosystem can be negatively impacted by the environmental variability that affects monitoring tools (BT and AT surveys in this case; Godø and Wespestad 1993; Godø 1994). To account for this impact we need to understand how the monitoring is affected by the environment and integrate environmental data into stock assessment process. We perceive our study as a step toward this goal. This topic requires further research that could concentrate on either including environmental variables in the process of estimating abundance indices or by integrating environmental variability into catchability estimates within stock assessment models. Regardless of the avenues that are pursued in the future, collection of environmental data during stock assessment surveys is essential.

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References

ADMB Project. 2009. AD Model Builder: automatic differentiation model builder. Developed by David Fournier and freely available from http://admb-project.org/.

Aglen, A. 1996. Impact of fish distribution and species composition on the relationship between acoustic and swept-area estimates of fish density. ICES J. Mar. Sci. **53**: 501–505. doi:10.1006/jmsc.1996.0072.

Aglen, A., Engås, A., Huse, I., Michalsen, K., and Stensholt, B.K. 1999. How vertical fish distribution may affect survey results. ICES J. Mar. Sci. **56**: 345–360. doi:10.1006/jmsc.1999.0449.

Alverson, D.L., and Pereyra, W.T. 1969. Demersal fish explorations in the northeastern Pacific Ocean — an evaluation of exploratory fishing methods and analytical approaches to stock size and yield forecasts. J. Fish. Res. Board Can. **26**(8): 1985–2001. doi:10.1139/f69-188.

Bartolino, V., Ciannelli, L., Bacheler, N.M., and Chan, K.S. 2011. Ontogenetic and sex-specific differences in density-dependent habitat selection of a marine fish population. Ecology, **92**: 189–200. doi:10.1890/09-1129.1. PMID:21560689.

Burnham, K.P., and Anderson, D.R. 2010. Model selection and multimodel inference. Springer, New York.

Christensen, N.L., Bartuska, A.M., Brown, J.H., Carpenter, S., D', Antonio, C., Francis, R., Franklin, J.F., MacMahon, J.A., Noss, R.F., Parsons, D.J., Peterson, C.H., Turner, M.G., and Woodmansee, R.G. 1996. The report of the Ecological Society of America committee on the scientific basis for ecosystem management. Ecol. Appl. **6**(3): 665–691. doi:10.2307/2269460.

Chuchukalo, V.I., Kuznetsova, N.A., and Napazakov, V.V. 1996. Seasonal distribution of euphausids in the Bering and Okhotsk Sea and adjacent waters of Pacific Ocean. Izv. TINRO, **119**: 256–281.

Clarke, A., and Johnston, N.M. 1999. Scaling of metabolic rate with body mass and temperature in fish. J. Anim. Ecol. **68**: 893–905. doi:10.1046/j.1365-2656.1999.00337.x.

Coyle, K.O., Chavtur, V.G., and Pinchuk, A.I. 1996. Zooplankton of the Bering Sea: a review of Russian-language literature. Ecology of the Bering Sea. Alaska Sea Grant Report No. 96-01, Fairbanks, Alaska. pp. 97–134.

DeRobertis, A., and Wilson, C. 2006. Walleye pollock respond to trawling vessels. ICES J. Mar. Sci. **63**(3): 514–522. doi:10.1016/j.icesjms.2005.08.014.

DeRobertis, A., and Wilson, C.D. 2011. Silent ships do not always encounter more fish (revisited): comparison of acoustic backscatter from walleye pollock recorded by a noise-reduced and a conventional research vessel in the eastern Bering Sea. ICES J. Mar. Sci. **68**(10): 2229–2239. doi:10.1093/icesjms/fsr146.

DeRobertis, A., Hjellvik, V., Williamson, N.J., and Wilson, C.D. 2008. Silent ships do not always encounter more fish: comparison of acoustic backscatter recorded by a noise-reduced and a conventional research vessel. ICES J. Mar. Sci. **65**(4): 623–635. doi:10.1093/icesjms/fsn025.

Dickson, W. 1993. Estimation of the capture efficiency of trawl gear. II: Testing a theoretical model. Fish. Res. **16**: 255–272. doi:10.1016/0165-7836(93)90097-Q.

Doray, M., Mahevas, S., and Trenkel, V.M. 2010. Estimating gear efficiency in a combined acoustic and trawl survey, with reference to the spatial distribution of demersal fish. ICES J. Mar. Sci. **67**(4): 668–676. doi:10.1093/icesjms/fsp277.

Egbert, G.D., and Erofeeva, S.Y. 2002. Efficient inverse modeling of barotropic ocean tides. J. Atmos. Oceanic Technol. **19**(2): 183–204. doi:10.1175/1520-0426(2002)019<0183:EIMOBO>2.0.CO;2.

Egbert, G.D., Bennett, A.F., and Foreman, M.G.G. 1994. Topex/Poseidon tides estimated using a global inverse model. J. Geophys. Res. Oceans, **99**(C12): 24821–24852.

Engås, A., and Godø, O.R. 1989. Escape of fish under the Norwegian sampling trawl and its influence on survey results. ICES J. Mar. Sci. **45**: 269–276. doi:10.1093/icesjms/45.3.269.

Engås, A., Godø, O.R., and Jørgensen, T. 2000. A comparison between vessel and trawl tracks as observed by the ITI trawl instrumentation. Fish. Res. **45**: 297–301. doi:10.1016/S0165-7836(99)00123-X.

Foote, K.G. 1983. Linearity of fisheries acoustics, with addition theorems. J. Acoust. Soc. Am. **73**: 1932–1940. doi:10.1121/1.389583.

Foote, K.G., Knudsen, H.P., Vestnes, G., MacLennan, D.N., and Simmonds, E.J. 1987. Calibration of acoustic instruments for fish density estimation: a practical guide. ICES Coop. Res. Rep. **144**: 1–57.

Godø, O.R. 1994. Factors affecting the reliability of groundfish abundance estimates from bottom trawl surveys. *In* Marine fish behaviour in capture and abundance estimation. *Edited by* A. Fernö and S. Olsen. Fishing New Books, Oxford. pp. 166–199.

Godø, O.R., and Engås, A. 1989. Swept area variation with depth and its influence on abundance indices of groundfish from trawl surveys. J. Northw. Atl. Fish. Sci. **9**: 133–139. doi:10.2960/J.v9.a12.

Godø, O.R., and Wespestad, V.G. 1993. Monitoring changes in abundance of gadoids with varying availability to trawl and acoustic surveys. ICES J. Mar. Sci. **50**: 39–51. doi:10.1006/jmsc.1993.1005.

Godø, O.R., Karp, W.A., and Totland, A. 1998. Effects of trawl sampling variability on precision of acoustic abundance estimates of gadoids from the Barents Sea and the Gulf of Alaska. ICES J. Mar. Sci. **55**: 86–94. doi:10.1006/jmsc.1997.0255.

Godø, O.R., Walsh, S.J., and Engås, A. 1999. Investigating density-dependent catchability in bottom-trawl surveys. ICES J. Mar. Sci. **56**: 292–298. doi:10.1006/jmsc.1999.0444.

Grumbine, R.E. 1994. What is ecosystem management? Conserv. Biol. **8**(1): 27–38. doi:10.1046/j.1523-1739.1994.08010027.x.

Handegard, N.O., and Tjøstheim, D. 2005. When fish meet a trawling vessel: examining the behaviour of gadoids using free-floating buoy and acoustic split-beam tracking. Can. J. Fish. Aquat. Sci. **62**(10): 2409–2422. doi:10.1139/f05-131.

Handegard, N.O., and Tjøstheim, D. 2009. The sampling volume of trawl and acoustics: estimating availability probabilities from observations of tracked individual fish. Can. J. Fish. Aquat. Sci. **66**(3): 425–437. doi:10.1139/F09-004.

Handegard, N.O., Michalsen, K., and Tjøestheim, D. 2003. Avoidance behaviour in cod (*Gadus morhua*) to a bottomtrawling vessel. Aquat. Living Resour. **16**: 265–270. doi:10.1016/S0990-7440(03)00020-2.

Harley, S.J., Myers, R.A., and Dunn, A. 2001. Is catch-per-unit-effort proportional to abundance? Can. J. Fish. Aquat. Sci. **58**(9): 1760–1772. doi:10.1139/f01-112.

Hilborn, R., and Walters, C.J. 1992. Quantitative fisheries stock assessment: Choice, dynamics and uncertainty. Chapman and Hall, New York.

Hjellvik, V., Michalsen, K., Aglen, A., and Nakken, O. 2003. An attempt at estimating the effective fishing height of the bottom trawl using acoustic survey recordings. ICES J. Mar. Sci. **60**: 967–979. doi:10.1016/S1054-3139(03)00116-4.

Hjellvik, V., Tjøstheim, D., and Godø, O.R. 2007. Can the precision of bottom trawl indices be increased by using simultaneously collected acoustic data? The Barents Sea experience. Can. J. Fish. Aquat. Sci. **64**(10): 1390–1402. doi:10.1139/f07-101.

Hoffman, J.C., Bonzek, C.F., and Latour, R.J. 2009. Estimation of bottom trawl catch efficiency for two demersal fishes, Atlantic croaker and white perch, in Chesapeake Bay. Mar. Coastal Fish.: Dynam. Manage. Ecosyst. Sci. **1**: 255–269.

Honkalehto, T., Ressler, P.H., Towler, R.H., and Wilson, C.D. 2011. Using acoustic data from fishing vessels to estimate walleye pollock (*Theragra chalcogramma*) abundance in the eastern Bering Sea. Can. J. Fish. Aquat. Sci. **68**(7): 1231–1242. doi:10.1139/f2011-050.

Hutchings, J.A. 1996. Spatial and temporal variation in the density of northern cod and a review of hypotheses for the stock's collapse. Can. J. Fish. Aquat. Sci. **53**(5): 943–962. doi:10.1139/f96-097.

Ianelli, J.N., Barbeaux, S., Honkalehto, T., Kotwicki, S., Aydin, K., and Williamson, N. 2009. Assessment of the walleye pollock stock in the Eastern Bering Sea, Section I. *In* Stock assessment and fishery evaluation report for the groundfish resources of the Bering Sea/Aleutian Islands regions. North Pac. Fish. Manage. Council, Anchorage, Alaska. pp. 49–148.

Karp, W.A., and Walters, G.E. 1994. Survey assessment of semipelagic gadoids: the example of walleye pollock, *Theragra chalcogramma*, in the eastern Bering Sea. Mar. Fish. Rev. **56**: 8–22.

Keith, G.J., Ryan, T.E., and Kloser, R.J. 2005. ES60adjust.jar. Java software utility to remove a systematic error in Simrad ES60 data. CSIRO Marine and Atmospheric Research, Castray Esplanade, Hobart, Tasmania, Australia.

Kimura, D.K., and Somerton, D.A. 2006. Review of statistical aspects of survey sampling for marine fisheries. Rev. Fish. Sci. **14**: 245–283. doi:10.1080/10641260600621761.

Kloser, R.J., Ryan, T.E., Williams, A., and Lewis, M. 2001. Development and application of a combined industry/scientific acoustic survey of orange roughy in the Eastern Zone: final report. CSIRO Mar. Res., Hobart, Australia FRDC Project-99/111.

Kotwicki, S., Buckley, T., Honkaletho, T., and Walters, G. 2005. Variation in the distribution of walleye pollock with temperature and implications for seasonal migration. Fish. Bull. **103**: 574–587.

Kotwicki, S., DeRobertis, A., von Szalay, P., and Towler, R. 2009. The effect of light intensity on the availability of walleye pollock (*Theragra chalcogramma*) to bottom trawl and acoustic surveys. Can J. Fish. Aquat. Sci. **66**(6): 983–994. doi:10.1139/F09-055.

Kutner, M., Nachtsheim, C., Neter, J., and Li, W. 2004. Applied linear statistical models. McGraw-Hill/Irwin, Homewood, Illinois.

Lauth, R.R. 2010. Results of the 2009 Eastern Bering Sea continental shelf bottom trawl survey of groundfish and invertebrate resources. US Dep. Commer. NOAA Tech. Memo. NMFS-AFSC-204.

Lawson, G.L., and Rose, G.A. 1999. The importance of detectability to acoustic surveys of semi-demersal fish. ICES J. Mar. Sci. **56**(3): 370–380. doi:10.1006/jmsc.1999.0476.

MacLennan, D.N., Fernandes, P.G., and Dalen, J. 2002. A consistent approach to definitions and symbols in fisheries acoustics. ICES J. Mar. Sci. **59**(2): 365–369. doi:10.1006/jmsc.2001.1158.

MacLennan, D.N., Copland, P.J., Armstrong, E., and Simmonds, E.J. 2004. Experiments on the discrimination of fish and seabed echoes. ICES J. Mar. Sci. **61**: 201–210. doi:10.1016/j.icesjms.2003.09.005.

Mangel, M., Talbot, L.M., Meffe, G.K., Agardy, M.T., Alverson, D.L., Barlow, J., Botkin, D.B., Budowski, G., Clark, T., Cooke, J., Crozier, R.H., Dayton, P.K., Elder, D.L., Fowler, C.W., Funtowicz, S., Giske, J., Hofman, R.J., Holt, S.J., Kellert, S.R., Kimball, L.A., Ludwig, D., Magnusson, K., Malayang, B.S., Mann, C., Norse, E.A., Northridge, S.P., Perrin, W.F., Perrings, C., Peterman, R.M., Rabb, G.B., Regier, H.A., Reynolds, J.E., Sherman, K., Sissenwine, M.P., Smith, T.D., Starfield, A., Taylor, R.J., Tillman, M.F., Toft, C., Twiss, J.R., Wilen, J., and Young, T.P. 1996. Principles for the conservation of wild living resources. Ecol. Appl. **6**(2): 338–362. doi:10.2307/2269369.

McQuinn, I.H., Simard, Y., Stroud, T.W.F., Beaulieu, J.L., and Walsh, S.J. 2005. An adaptive, integrated "acoustic-trawl" survey design for Atlantic cod (*Gadus morhua*) with estimation of the acoustic and trawl dead zones. ICES J. Mar. Sci. **62**(1): 93–106. doi:10.1016/j.icesjms.2004.06.023.

Mello, L.G.S., and Rose, G.A. 2009. The acoustic dead zone: theoretical vs. empirical estimates, and its effect on density measurements of semi-demersal fish. ICES J. Mar. Sci. **66**(6): 1364–1369.

Michalsen, K., Godø, O.R., and Fernö, A. 1996. Diel variation in the catchability of gadoids and its influence on the reliability of abundance indices. ICES J. Mar. Sci. **53**(2): 389–395. doi:10.1006/jmsc.1996.0054.

O'Driscoll, R.L. 2003. Determining species composition in mixed-species marks: an example from the New Zealand hoki (*Macruronus novaezelandiae*) fishery. ICES J. Mar. Sci. **60**: 609–616. doi:10.1016/S1054-3139(03)00034-1.

O'Driscoll, R., Rose, G., and Andersen, J. 2002. Counting capelin: a comparison of acoustic density and trawl catchability. ICES J. Mar. Sci. **59**: 1062–1071. doi:10.1006/jmsc.2002.1262.

Ona, E., and Godo, O.R. 1990. Fish reaction to trawling noise: the significance for trawl sampling. Rapp. P.-V. Reun. Cons. Int. Explor. Mer, **189**: 159–166.

Ona, E., and Mitson, R.B. 1996. Acoustic sampling and signal processing near the seabed: the dead zone revisited. ICES J. Mar. Sci. **53**: 677–690. doi:10.1006/jmsc.1996.0087.

Patel, R., Pedersen, G., and Ona, E. 2009. Inferring the acoustic dead-zone volume by split-beam echo sounder with narrow-beam transducer on a noninertial platform. J. Acoust. Soc. Am. **125**: 698–705. doi:10.1121/1.3050325. PMID: 19206847.

Ressler, P.H., De Robertis, A., Warren, J.D., Smith, J.N., and Kotwicki, S. 2012. Developing an acoustic survey of euphausiids to understand trophic interactions in the Bering Sea ecosystem. Deep-Sea Res. II. **65–70**: 184–195. doi:10.1016/j.dsr2.2012.02.015.

Rivoirard, J., Simmonds, K., Foote, P., and Bez, N. 2000. Geostatistics for estimating fish abundance. Iowa State Press, Blackwell, Iowa.

Rooper, C.N., Hoff, G.R., and DeRobertis, A. 2010. Assessing habitat utilization and rockfish (*Sebastes* spp.) biomass on an isolated rocky ridge using acoustics and stereo image analysis. Can J. Fish. Aquat. Sci. **67**(10): 1658–1670. doi:10.1139/F10-088.

Rose, C.S., and Nunnallee, E.P. 1998. A study of changes in groundfish trawl catching efficiency due to differences in operating width, and measures to reduce width variation. Fish. Res. **36**: 139–147. doi:10.1016/S0165-7836(98)00099-X.

Rose, G.A. 2003. Monitoring coastal northern cod: towards an optimal survey of Smith Sound, Newfoundland. ICES J. Mar. Sci. **60**(3): 453–462. doi:10.1016/S1054-3139(03)00044-4.

Ryan, T.E., and Kloser, R.J. 2004. Quantification and correction of a systematic error in Simrad ES60 echosounders. ICES FAST, Gdansk. Copy available from CSIRO Marine and Atmospheric Research, Hobart, Australia.

Smith, K.R., and McConnaughey, R.A. 1999. Surficial sediments of the eastern Bering Sea continental shelf: EBSSED database documentation. US Dep. Commer. NOAA. Tech. Memo NMFS-AFSC-104.

Somerton, D.A. 2004. Do Pacific cod (*Gadus macrocephalus*) and walleye pollock (*Theregra chalcogramma*) lack a herding response to the doors, bridles, and mud clouds of survey trawls? ICES J. Mar. Sci. **61**: 1186–1189. doi:10.1016/j.icesjms.2004.06.003.

Somerton, D.A., and Weinberg, K.L. 2001. The affect of speed through the water on footrope contact of a survey trawl. Fish. Res. **53**: 17–24. doi:10.1016/S0165-7836(00)00272-1.

Somerton, D., Ianelli, J., Walsh, S., Smith, S., Godø, O., and Ramm, D. 1999. Incorporating experimentally derived estimates of survey trawl efficiency into the stock assessment process: a discussion. ICES J. Mar. Sci. **56**: 299–302. doi:10.1006/jmsc.1999.0443.

Spencer, P.D. 2008. Density-independent and density-dependent factors affecting temporal changes in spatial distributions of eastern Bering Sea flatfish. Fish. Oceanogr. **17**(5): 396–410. doi:10.1111/j.1365-2419.2008.00486.x.

Springer, A.M., McRoy, C.P., and Turco, K.R. 1989. The paradox of pelagic food webs in the northern Bering Sea – II. Zooplankton communities. Cont. Shelf Res. **9**(4): 359–386. doi:10.1016/0278-4343(89)90039-3.

Stauffer, G. 2004. NOAA protocols for groundfish bottom trawl surveys of the Nation's fishery resources. US Dep. Comer. NOAA. Tech. Memo. NMFS-F/SPO-65.

Traynor, J.J. 1996. Target-strength measurements of walleye pollock (*Theragra chalcogramma*) and Pacific whiting (*Merluccius productus*). ICES J. Mar. Sci. **53**(2): 253–258. doi:10.1006/jmsc.1996.0031.

von Szalay, P.G., Somerton, D.A., and Kotwicki, S. 2007. Correlating trawl and acoustic data in the eastern Bering Sea: a first step toward improving biomass estimates of walleye pollock (*Theragra chalcogramma*) and Pacific cod (*Gadus macrocephalus*)? Fish. Res. **86**: 77–83. doi:10.1016/j.fishres.2007.05.005.

von Szalay, P.G., and Somerton, D.A. 2009. A comparison of acoustic backscatter between a trawling and a free-running vessel for eastern Bering Sea walleye pollock (*Theragra chalcogramma*). Fish. Res. **96**: 223–229. doi:10.1016/j.fishres.2008.11.009.

Walsh, J.J., and McRoy, C.P. 1986. Ecosystem analysis in the southeastern Bering Sea. Cont. Shelf Res. **5**: 259–288. doi:10.1016/0278-4343(86)90018-X.

Walters, C., and Maguire, J.J. 1996. Lessons for stock assessment from the northern cod collapse. Rev. Fish Biol. Fish. **6**: 125–137.

Walters C.J. and Martell, S. 2004. Fisheries ecology and management. Princeton University Press, Princeton, New Jersey.

Weinberg, K.L., and Kotwicki, S. 2008. Factors influencing net width and sea floor contact of a survey bottom trawl. Fish. Res. **93**: 265–279. doi:10.1016/j.fishres.2008.05.011.

Wentworth, C.K. 1922. A scale of grade and class terms for clastic sediments. J. Geol. **30**: 377–392. doi:10.1086/622910.

Wilberg, M.J., Thorson, J.T., Linton, B.C., and Berkson, J. 2010. Incorporating time-varying catchability into population dynamic stock assessment models. Rev. Fish. Sci. **18**: 7–24.

Zhao, X., and Ona, E. 2003. Estimation and compensation models for the shadowing effect in dense fish aggregations. ICES J. Mar. Sci. **60**: 155–163. doi:10.1006/jmsc.2002.1319.